Downhole acceleration detection of poor drilling performance related to bit damage

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ABSTRACT

Improving drilling performance continues to be an active topic of research, not only for the oil and gas industry, but also for emerging industries such as geothermal. Real-time drilling monitoring enables operational decisions that can save significant drilling costs. Monitoring strategies generally utilize surface measurements to detect drilling dysfunctions that degrade drilling performance, but deep or highly deviated wells often require downhole sensors to monitor drill string dynamics effectively. Downhole data does have limitations related to telemetry and sensor operating limits, specifically temperature in the context of geothermal. A potential alternative monitoring solution is bit-source seismic-while-drilling (BSWD), where surface sensors are utilized to detect drilling dysfunctions. The goal of the research presented here is to use the downhole accelerometer data to understand the source characteristics of the bit for future utilization of BSWD. Accelerometer data from 2 different drilling intervals are evaluated along with drilling performance to establish acceleration attributes that could be relevant for understanding the bit as a seismic source. Cross plots of acceleration attributes for the 2 drilling intervals show similar trends even though they have several physical and operational differences. High tangential maximum acceleration values for both datasets correspond to the end of the bit run, approximately the last 15feet of drilling prior to the decision to pull the bit. While both bits incurred significant damage, increased axial vibrations are observed for the bit with more severe damage. In the context of BSWD, the increase in tangential and axial vibrations are expected to result in higher wavefield energy propagating to the surface. Understanding of the various wavefield amplitudes on the BSWD data could be a potential tool to identify drilling events that result in significant bit damage.

INTRODUCTION

Drilling technology plays a pivotal role in numerous subsurface industries. While primarily associated with oil and gas, drilling is a key enabling technology for upcoming industries that will help meet energy demands and decarbonization goals, such as geothermal and CO2 storage. Despite more than a century of technological advancements, research and development efforts remain highly dynamic and span all aspects of the drilling process from novel drilling techniques (Houde et al., 2021, Rossi et al., 2020) to automation and detection using machine learning (Gengsheng et al., 2022; Løken et al., 2020, Baumgartner and Oort, 2014). One of the objectives of continued research is drilling optimization, which can be summarized as drilling in the most efficient way possible to meet all drilling objectives while minimizing overall drilling costs. This requires not only drilling through the rock as quickly as possible, but also maintaining system integrity such as bit life. Unplanned bit changes are a costly activity that can add many days to a drilling operation. The effectiveness of the drill bit to destroy rock not only depends on the drill bit condition, but also the downhole system dynamics (Ertas et al., 2014). Supplying sufficient weight to the bit and avoiding significant drill string vibrations can have a drastic effect on rock penetration rates.

Real-time drilling performance can be monitored using two different data sources, surface and downhole measurements. Surface rig data includes the operating parameters and system responses measured at the surface such as hook load, rotary torque, differential pressure, etc. While surface measurements can be used to model and predict drill string dynamics downhole (Shor et al, 2014; Saadeldin et al, 2022), system responses from downhole can be undetectable at the surface due to energy stop bands in the drilling assembly (Zhang et al., 2023) or friction in deviated and deep wells due to the attenuation and energy losses along the drill string (Lee, 1991). To overcome this, sensors can be mounted downhole on the system, such as the drill bit or the Bottom Hole Assembly (BHA). While this does provide local measurements of the downhole dynamics, retrieving the information for real-time decisions requires transmission of the downhole measurements to the surface. Mud pulse telemetry is a common method to supply measurement while drilling to the surface but is limited to small bandwidth transmission and can suffer from distorted pressure pulses in the mud system (Mwachaka et al., 2019). Wired pipe provides electromagnetic data transmission with larger bandwidth but is costly. Downhole processing is an option to condense the high frequency signal to the required bandwidth for transmission (Johnson et al., 2023). When real-time transmission is not considered an option, downhole sensor data can be recorded on memory and retrieved at the end of the bit run when the BHA is tripped out of the hole. Additional instrument limitations are introduced when considering the high temperature resource targeted by geothermal drilling activities. High temperature downhole sensors will be required for effective real-time drilling monitoring.

This research is motivated by a novel application of bit source seismic-while-drilling (BSWD) data in real-time drilling operation (Figure 01). Bakulin et al. (2020) demonstrated the pseudo real-time acquisition of BSWD for a well drilled down to over 9000 feet. Data from wireless geophones at the surface were transmitted and recorded at nearly 1-minute intervals and were demonstrated to provide sufficient data quality for typical SWD applications such as time-depth calibration, vertical seismic profile corridor stack, and look-ahead of the bit evaluation down to depths around 6000 feet. The extension of their work would be to utilize the BSWD data to contribute to real-time drilling performance monitoring. Utilizing sensors at the surface could alleviate the need for high temperature sensors and borehole data transmission. In this research, downhole vibration data that were acquired on memory are analyzed to characterize and differentiate the vibration character for different drilling intervals. The goal is to inform future utilization of BSWD analysis and interpretation for real-time drilling monitoring and identification of drilling dysfunctions such as severe vibrations and bit damage.

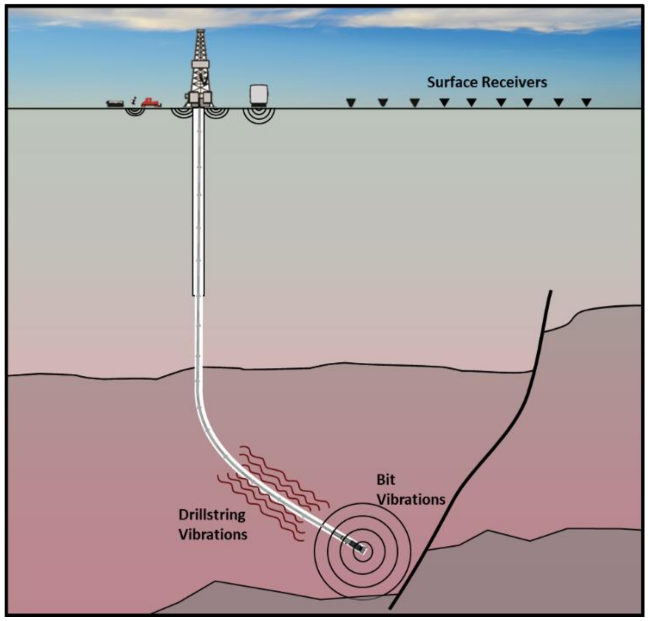

FIG. 01. Bit-source seismic-while-drilling data measures wavefields at the surface created by the drill string and bit. Illustration modified from Wang et al. 2015.

DOWNHOLE ACCELEROMETER DATA

Downhole accelerometers can be mounted in various location on the BHA to measure the complex dynamics near the bit during drilling. With sampling rates ranging from 10's of Hertz to kilohertz, the high frequency responses of the drill string and bit can be better characterized than using surface drilling data alone (Hohl et al., 2016, Johnson et al., 2023). Downhole accelerometers can be 1 to 3-components and measure displacement along the axial, tangential, and lateral directions. The example snippet of 3-compononent acceleration data in Figure 02 shows 2 hours of data sampled at 400Hz measured as a coefficient times the acceleration of gravity (i.e. 20g = 20 x 9.8m/s2). The acceleration data was recorded on memory downhole and retrieved at the surface. Before the downhole data can be combined with the surface drilling data, the data is processed using custom python workflows. The workflow created for the preprocessing includes: loading native binary format data and conversion to feather format data (Apache, 2023) for quick saving and loading, time alignment of the downhole times to account for time misalignment and instrument drift, resampling to constant sampling frequency to account for cycle skipping, and attribute extraction to match surface drilling sampling of 1 Hertz. Figure 03 shows an example of the 1-second attributes over a 30 second window of high frequency data.

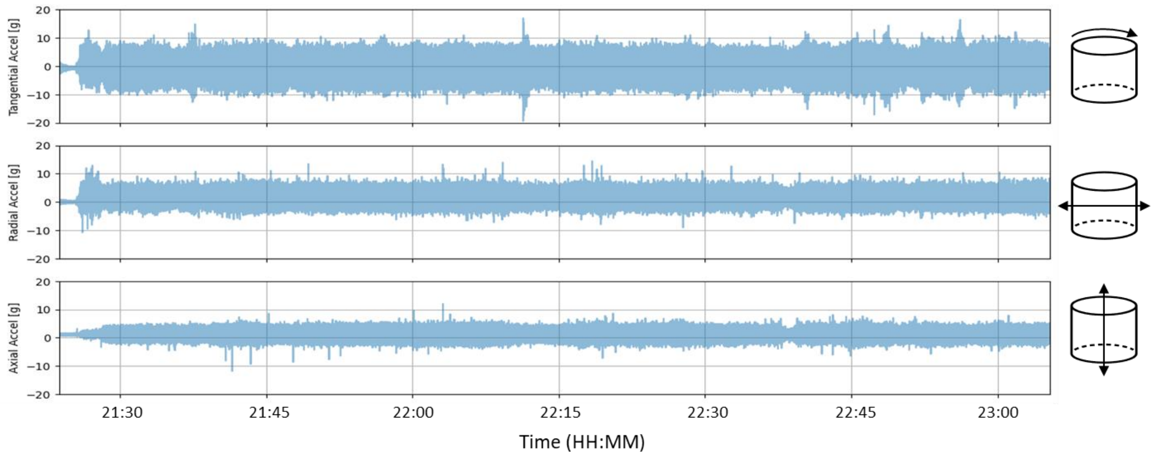

FIG. 02. The 3-compenents of acceleration capture the tangential, radial, and axial vibrations of the BHA. Orientations of accelerations with respect to the drill string are illustrated on the right.

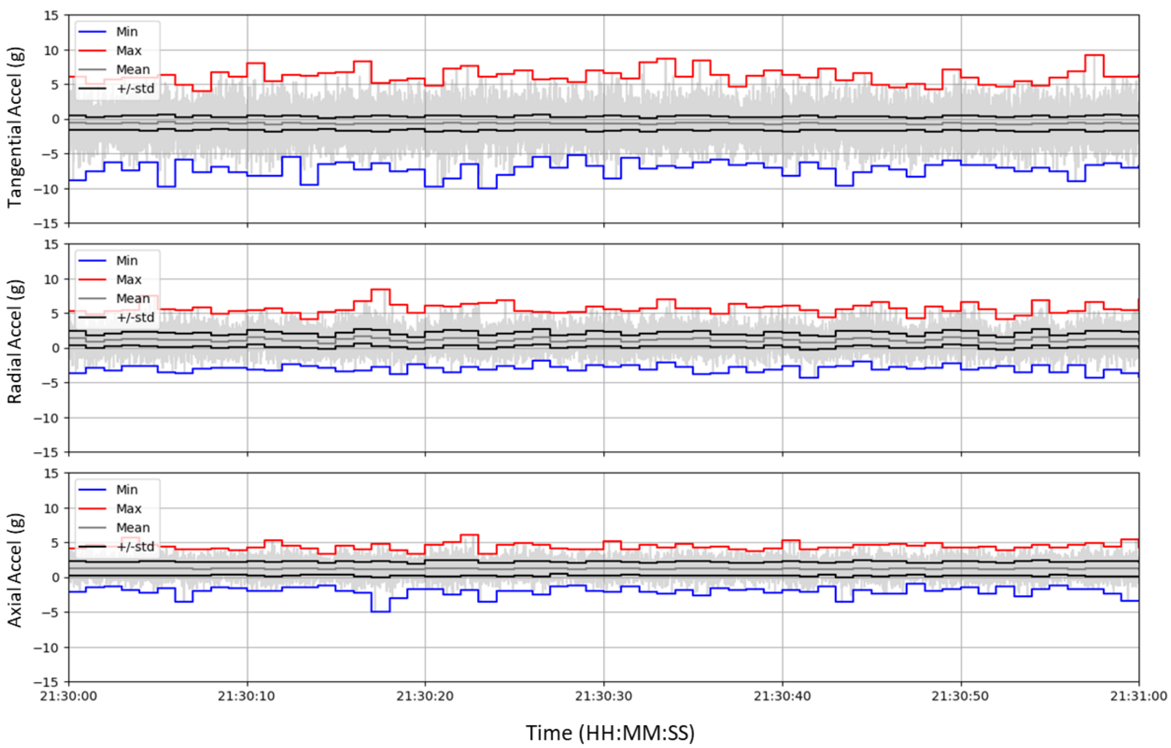

FIG. 03. A zoom into the 30 seconds of acceleration data with the typical amplitude attributes of minimum (blue), maximum (red), mean (grey), and standard deviation (black) for each second of data to match the 1Hz sampling rate of the drilling data.

In this study, two high frequency downhole acceleration data sets are evaluated for potential relationships that can be used to isolate drilling performance windows. A couple of the questions to be explored are: 1) can attributes and trends in the acceleration data consistently separate good drilling performance from poor drilling performance and 2) how does the downhole vibration data inform future BSWD analysis?

The drilling intervals, further referred to as BHA01 and BHA02, have several similarities and differences (Table 1). The most notable similarities are: both BHA's used polycrystalline diamond compact (PDC) bits with a downhole mud motor, and both BHA's had the same model of accelerometer mounted in a similar location recording full waveform on memory. There are several notable differences between the two BHA's including the bit size, drilled depth interval, and drilling operational strategies. The operational drilling strategy for BHA02 was ROP limited drilling with iterations of slide drilling, but not for BHA01. ROP limited drilling enforces a target rate that is maintained by adjusting drilling parameters. Slide drilling is performed by reducing the surface rotation of the drill string to slow oscillating rotations and drilling primarily using the downhole mud motor.

Table 1. BHA run parameter comparison for BHA01 and BHA02.

BHA Run	Downhole Sensor	Sensor Location	Bit type/size (inches)	Downhole Mud Motor	Depth Interval (ft)	ROP Limited	Slide Drilling
BHA01	VSS + Temp HF in-bit	Shank	PDC/12.25	Yes	8027 - 9240	No	No
BHA02	VSS + Temp HF in-bit	Shank	PDC/8.5	Yes	13858 -14494	Yes	Yes

The drilling performance as a measure of ROP for each BHA run are shown in Figure 04. The overall performance profiles for the BHA's are quite different. For BHA01, ROP drops from near 100 feet/hour to 25 feet/hour over 400 feet of drilling, then continues at less than 50 feet/hour until the last 200 feet. The end of the run shows a sharp decrease in ROP to below 25 feet/hour. BHA02 maintains a ROP above 100 feet/hour for over 600 feet before showing a decrease to below 25 feet/hour after the last slide drilling interval. Slide drilling intervals are consistently below 50 feet/hour. In the next section, downhole acceleration attributes are analyzed for both BHA's. Surprisingly, considering all the differences, there are several similarities observed in the acceleration data relationships.

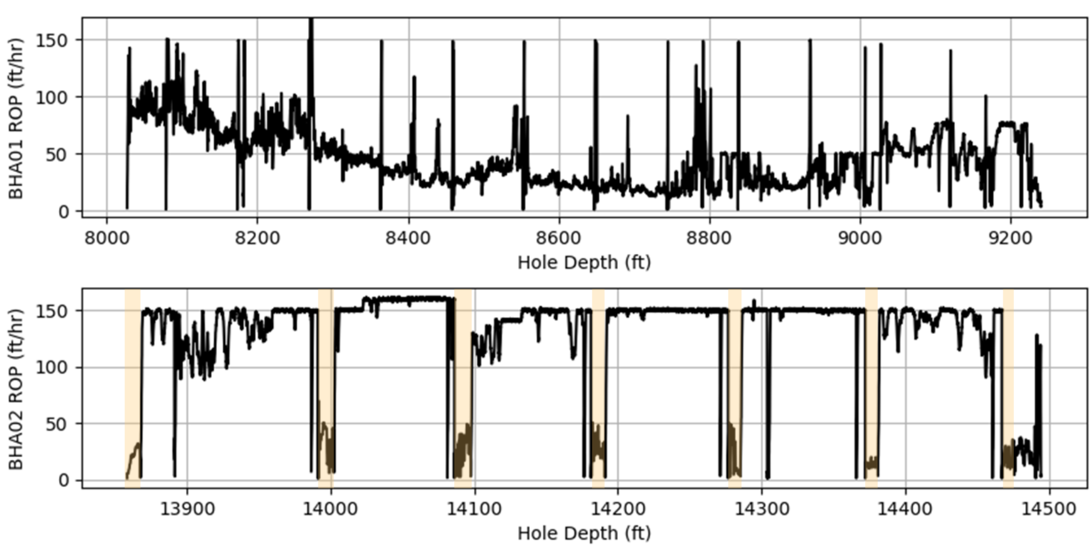

FIG. 04. Drilling performance measured as Rate of Penetration (ROP) is plotted for BHA01 and BHA02. Depth intervals of slide drilling are highlighted with orange for BHA02.

Vibration Analysis

The 3-component accelerometer data is recorded continuously during the drilling operation. After preprocessing, the down sampled attribute values for the different components of vibration can be cross plotted to see the relative contribution of different vibration modes. Figure 05 shows the tangential, axial, and radial maximum amplitude (MxAmp) and standard deviation (STD) attribute cross plots for full depth of the BHA01 run. Well defined trends and clusters exist on several of the attribute cross plots. The linear trends in the STD cross plots appear to separate high and low rates of ROP. Figure 06 shows the corresponding depths in the borehole for the linear trends observed on the Tangential and axial STD cross plot in Figure 05. The trend of high Tangential STD and low axial STD values corresponds to the end of the bit run around 9200 feet hole depth where the ROP rates drop below 20 feet/hour. The trend of high axial STD values corresponds to the beginning of the bit run where ROP rates decrease from above 100 feet/hour to less than 40 feet/hour.

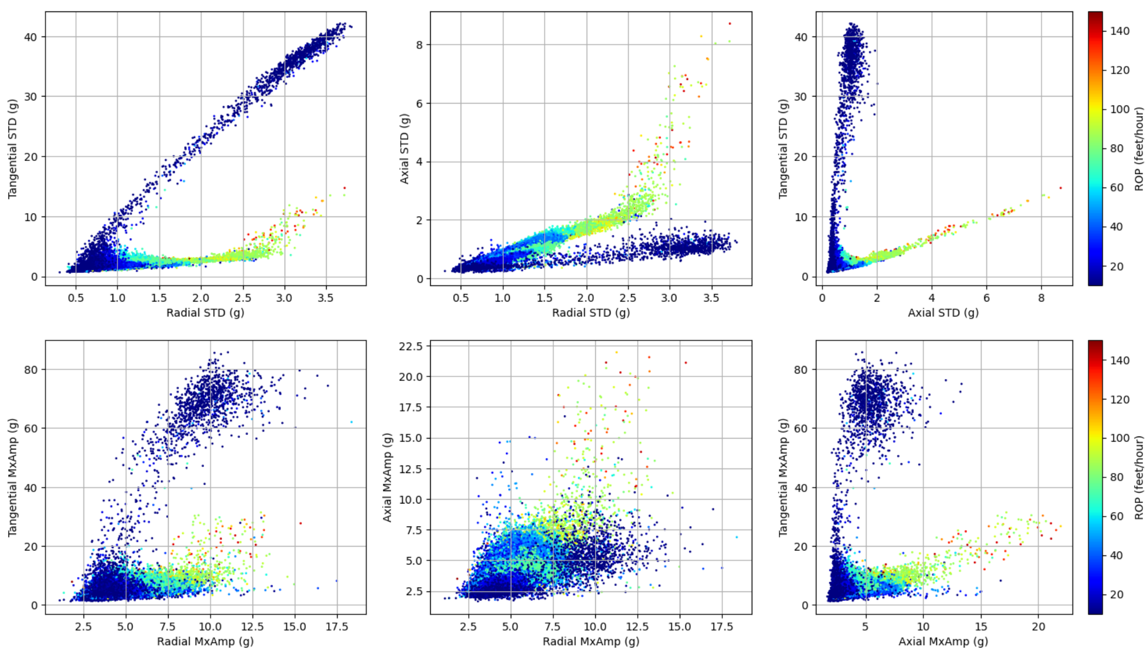

FIG. 05. Cross plots of the maximum amplitude (MxAmp) and standard deviation (STD) for BHA01 separate trends and clusters related to ROP performance.

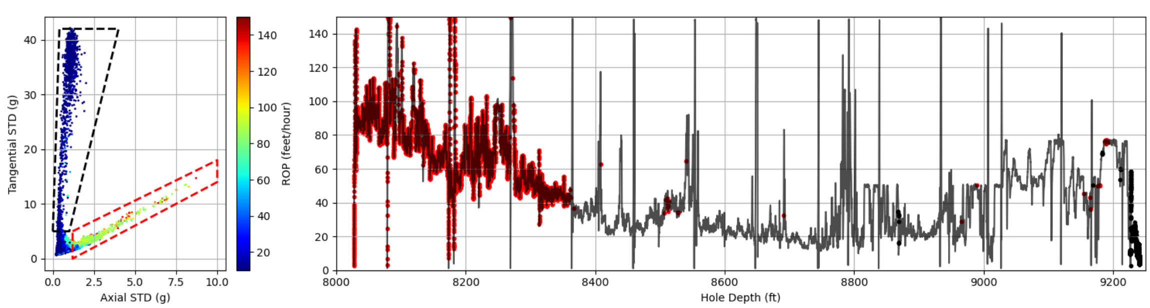

FIG. 06. Two distinct trends of tangential and axial acceleration standard deviations (STD) on the cross plot separate the early drilling depths on the plot on the right where ROP rates decrease from

100 feet/hour to less than 40 feet/hour (red) and late drilling depths before the bit was pulled out of hole with ROP rates dropping below 20 feet/hour (black).

Figure 07 shows the tangential, axial, and radial maximum amplitude (MxAmp) and standard deviation (STD) attribute cross plots for BHA02. Similar trends as observed for BHA01 can be seen in the cross plots for BHA02. The ROP performance for this section of drilling is generally good with the majority of the section being drilled at above 100 feet/hour. Figure 08 shows the corresponding depths in the borehole for the clusters of data observed on the Tangential and Axial STD cross plot in Figure 07. The trend of high tangential STD values corresponds to the end of the bit run (black), while the trend of increasing axial STD values and low tangential STD values (red) corresponds to a majority of the rest of the drilled section, including transitions to slide drilling intervals.

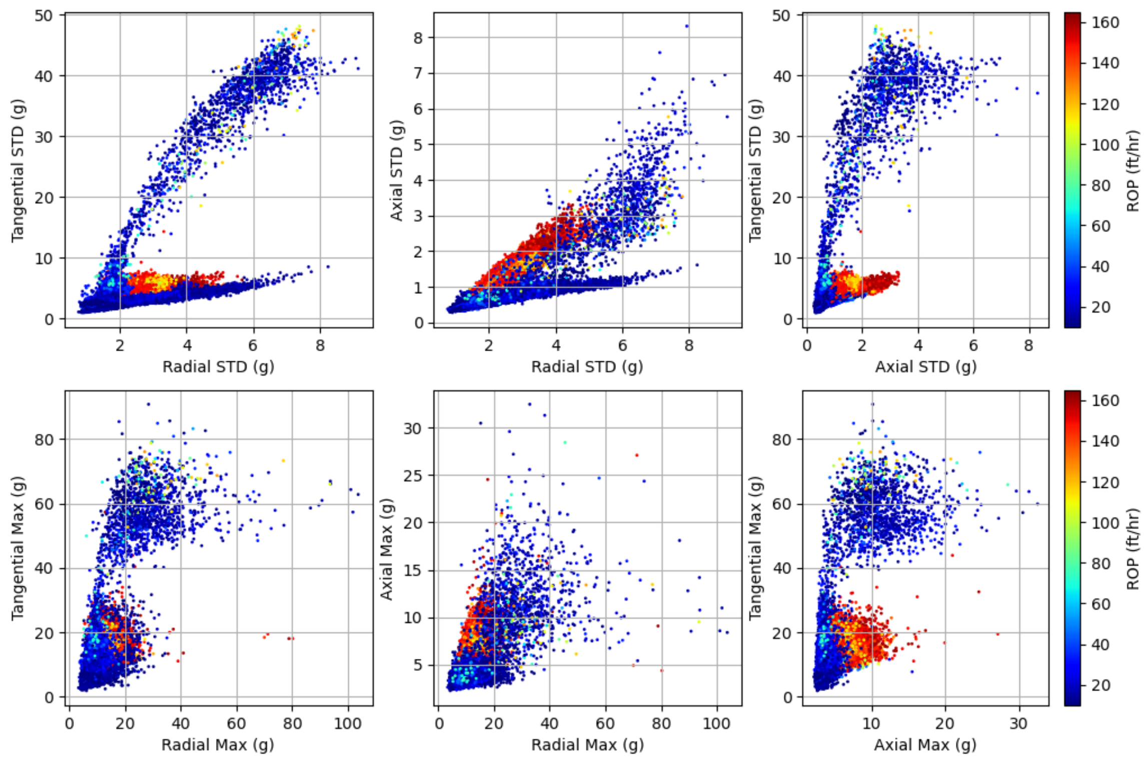

FIG. 07. Cross plots of the maximum amplitude (MxAmp) and standard deviation (STD) for BHA02 colored by ROP.

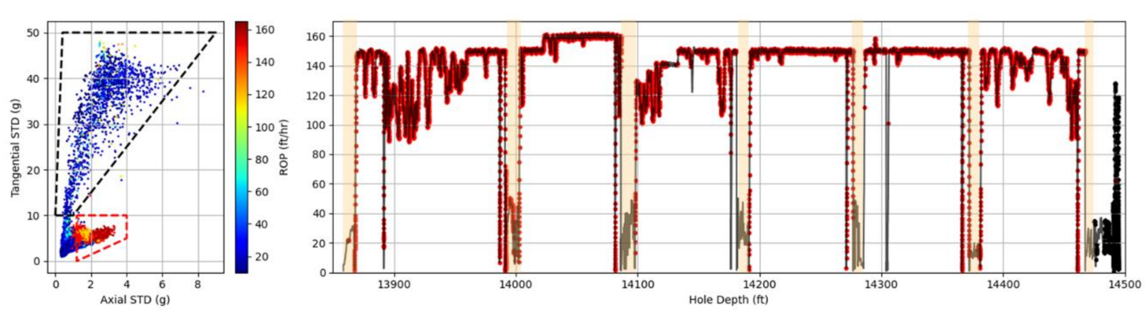

FIG. 08. Similar to BHA01, the two trends of tangential and axial acceleration standard deviations (STD) on the cross plot separate sections of drilling for BHA02. The rotary drilling performance for

BHA02 remains high throughout the bit run until after the last slide drilling section at around 14480 feet hole depth. The trend of high tangential STD values (black) isolates the low ROP at the end of the bit run. The trend of increased axial STD values and low tangential STD values (red) capture the majority of the section drilled with high ROP.

While characterization of acceleration STD could be useful for real-time monitoring with downhole data, the potential utilization for BSWD signal analysis is unclear. Alternatively the maximum amplitude attribute could provide more insight into the drill string and bit source characteristics for BSWD. Figure 09 shows the tangential and axial MxAmp cross plot BHA01. While the high values of tangential MxAmp (black) isolate the end of the bit run, the trend of increased axial MxAmp and lower tangential MxAmp (red) primarily isolates just the beginning of the bit run.

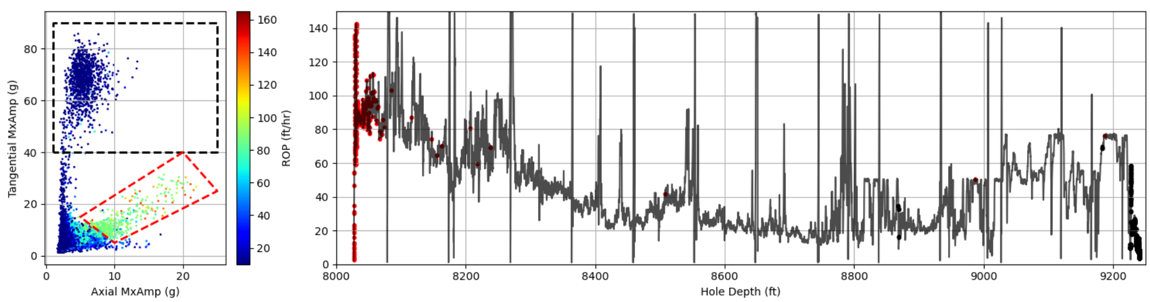

FIG. 09. The cross plot of tangential and axial acceleration maximum amplitude (left) for BHA01 shows clusters of data associated with the beginning (red) and end (black) of the bit run as highlighted on the ROP and hole depth data (right).

The maximum amplitude cross plot for the BHA02 tangential and axial acceleration has a distinct cluster of high tangential MxAmp (black) that isolates the end of the bit run. The high ROP cluster (red) does not separate as a trend, but instead sits offset with slightly higher axial MxAmp values around 10g.

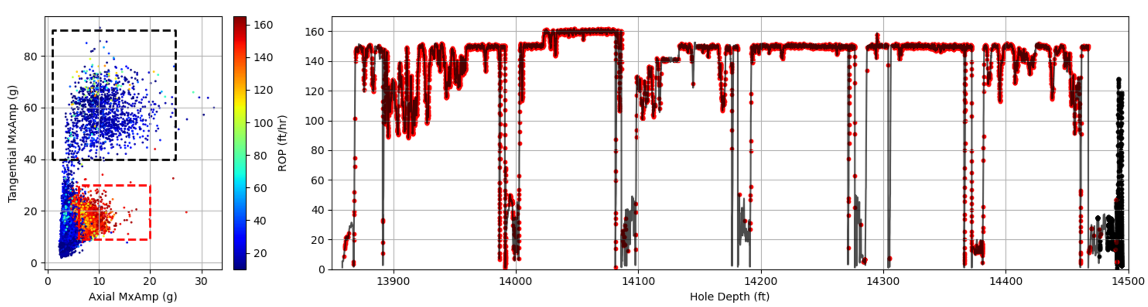

FIG. 10. The cross plot of tangential and axial acceleration maximum amplitude (left) for BHA02 shows clusters of data associated with the majority of the bit run (red) and end of the bit run (black) as highlighted on the ROP and hole depth data (right).

Comparing the tangential and axial MxAmp for both BHA's, the clusters of data with high tangential MxAmp and associated with the end of the bit run generally sit above a cutoff of 40g tangential MxAmp (Figure 11). Above this threshold, BHA01 axial MxAmp, plotted along the x-axis, cluster below 10g, while BHA02 has a larger spread that extends beyond 15g.

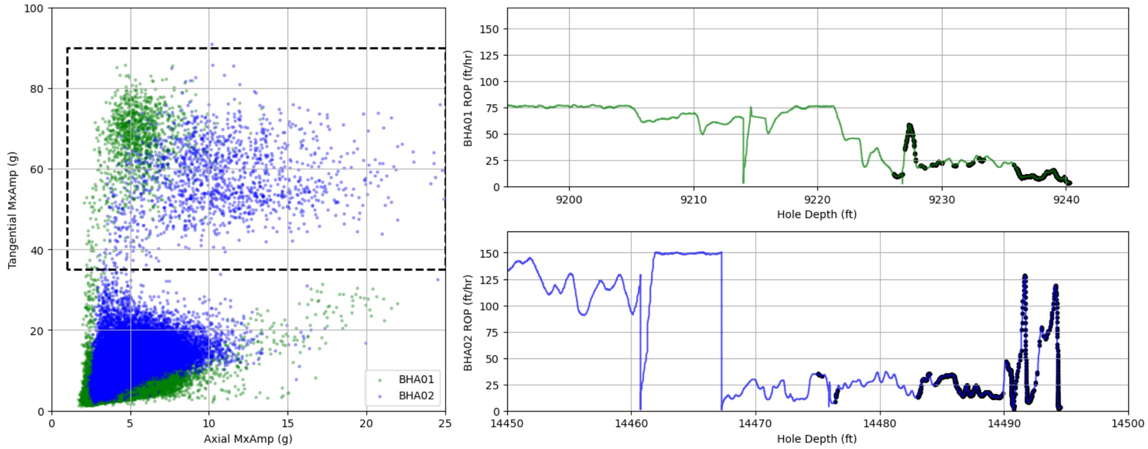

FIG. 11. The crossplot for tangential and axial MxAmp for BHA01 (green) and BHA02 (blue) shows that the clusters of data associated with the end of the bit run (black) occupy the same range of tangential MxAmp.

DISCUSSION

Many authors have demonstrated that downhole high frequency acceleration data can be used to diagnose drilling vibrations (Sigiura and Jones, 2020). The acceleration data from the two BHA's presented here show consistent clustering of data that separates drilling performance windows. The cross plots of standard deviation and maximum amplitude attributes have distinct trends of increased tangential values (black) that correspond to poor drilling performance at the end of the bit run (Figure 12). Within this subset (black ovals), the axial values for BHA02 are much higher and have a larger spread than BHA01. A potential explanation for this difference could be related to the extent of damage to each bit, with much larger damage for BHA02, which could be responsible for the increased axial vibrations. It's common in drilling to monitor for higher tangential vibrations in the bottomhole assembly, as the indication of either drill bit dysfunction, or formation change. In this case, the memory data indicated minor variation in the drilling environment (including formation, drilling parameters, and wellbore geometry). Therefore, the increased tangential acceleration attributes indicated the onset or extent of bit damage.

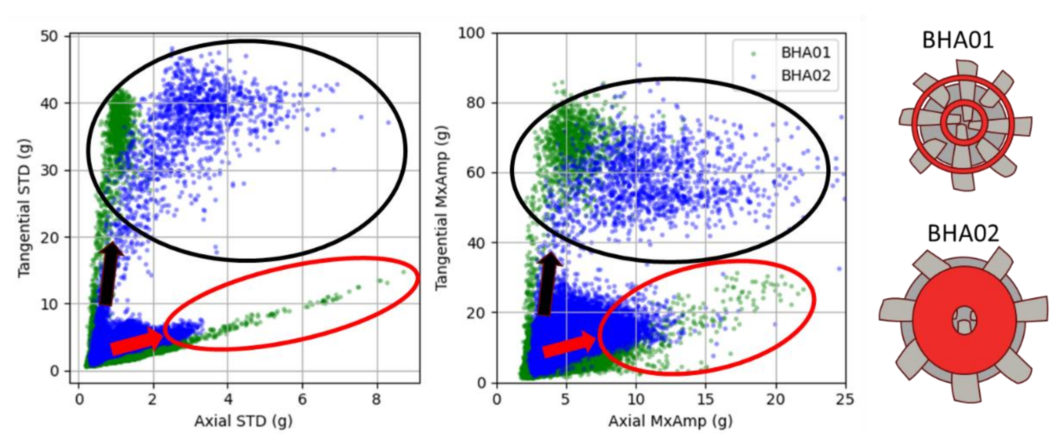

FIG. 12. The STD and MxAmp cross plots of tangential and axial data for the 2 BHA's have similar trends of poor drilling performance with high tangential values (black). The spread of axial values

within these clusters could be related to the extent of bit damage experienced by the bit. Increased drilling performance is associated with increased axial values with lower associated tangential values (red). Schematic representations of the extent of damage to the bit face for the BHA's are shown on the right with the red rings.

The trend of high tangential MxAmp could be useful for BSWD monitoring and detection. Tangential and axial accelerations at the bit will be transmitted to the rock via interaction at the bit-rock interface (Figure 13). Source radiation patterns for roller-cone bits have been modeled to include compressional (P), vertical shear (SV), and horizonal shear (SH) wavefields (Rector and Hardage, 1992). The P wavefield radiates in the axial direction ahead of the bit, while SV and SH wavefields radiate in a horizontal plane perpendicular to the axial direction. Auriol et al. (2020) suggest that axial interaction of the bit and rock will produce P and SV wavefields, while rotation of the bit will produce SH. The amplitudes of the different wavefields depend on the rock destruction mechanism (i.e. compressive versus shear failure), the accelerations of the bit (i.e. axial vs tangential), and the Poisson's ratio of the rock (Rector and Hardage, 1992). Previous authors have proposed that because PDC bits cut the rock through shear failure, fewer axial vibrations are generated compared to a roller cone bit (Malusa et al., 2003). Based on the acceleration relationships demonstrated in these datasets, tangential accelerations will likely be the largest magnitude component of acceleration during well-behaved PDC drilling (i.e. no significant vibrations related to dysfunction).

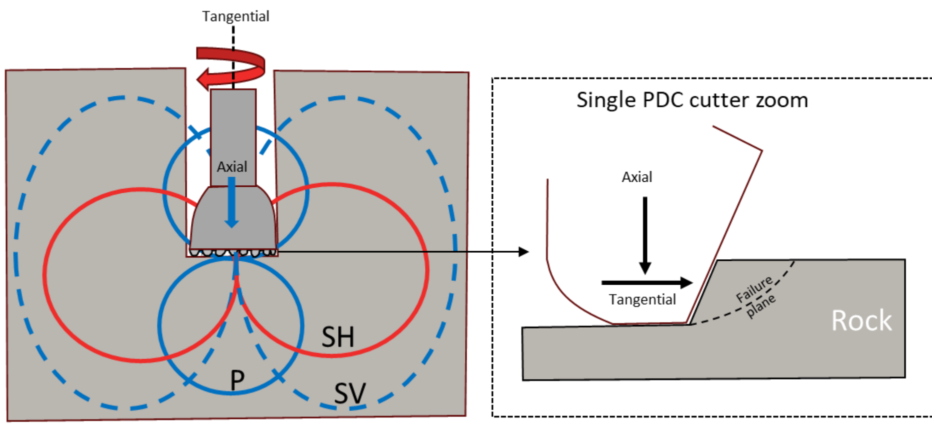

FIG. 13. The wavefields generated from the axial and tangential forces at the bit-rock interface (left) include compressional (P) vertical shear, and horizontal shear (SH). The zoom view (right) of a single cutter for a PDC bit shows the expected forces on the cutter and a hypothetical shear failure plane.

The analysis of these 2 BHA runs suggests that there should be differences in the bit source wavefield that could be associated to drilling performance. The potential application of BSWD monitoring would be targeted at observing increased shear wavefield energy that would indicate high values of tangential acceleration. The next steps of this research will include analysis of additional bottomhole assemblies to see if similar relationships in the acceleration data hold. In general, frequency spectrums of the 6-axis high frequency downhole accelerometer data should be investigated to see what additional attributes could be used to isolate drilling performance windows in the beginning of each run, and towards the end of each run. This frequency spectrum analysis (FSA) could be applied in real-time drilling dynamics analysis to proactively (before the failure) detect the drill bit dysfunction in drilling. If the FSA model is calibrated with standardized bottomhole assemblies in the beginning of the drilling program, then this model can be used to compensate the bit source wavefield deterioration from the drill bit in the post-well BSWD interpretation of new data, and serve as a real-time indicator for the onset bit damage. For the latter, it will provide substantial drilling cost reduction, as the bit can be pulled out of the hole in a repairable condition as in the BHA1, rather than being damaged beyond repair as in the BHA2.

ACKNOWLEDGEMENTS

We thank the sponsors of CREWES for their continued support. This work was funded by CREWES industrial sponsors, NSERC (Natural Science and Engineering Research Council of Canada) through the CRSNG 561118-20, and Alberta Innovates through the grant 212200496. We also thank Eavor Technologies for the technical discussions and providing drilling data and accelerometer data. Thank you to Louis Chabot for technical discussions.

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